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Safe Distances From a High-Energy Capacitor Bank for Ear and Lung Protection

by Charles R. Hummer, Richard J. Pearson, and Donald H. Porschet

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14. ABSTRACT
High-energy capacitor banks may have a significant amount of residual energy after a test or malfunction. This presents distinct hazards from shock, arc flash, projectile, and lung/ear/eye when the capacitor bank is to be manually rendered safe. Although standard operating procedures address most of these hazards, the danger to the ear and lung from the over-pressure of an arc blast has not been satisfactorily established. This lung and ear danger is addressed in this report, along with proposed mitigation techniques.

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arc flash, shock, high-energy capacitors, ear protection, lung protection

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1. Introduction

The normal operation of a high-energy capacitor bank follows a series of general tasks with the first step being the removal of any and all hard electrical shorts placed across each capacitor. The area around the capacitor bank and the experimental area are then vacated and secured from personnel entering whereupon the capacitor bank is charged to its desired state and then discharged through the experiment. If the experiment proceeds as planned there should be little to no residual energy in the capacitor bank. Still, the capacitor bank should be discharged either manually or remotely, depending on the energy levels, and a hard short once again placed across the capacitors. The process of placing the capacitor in a safe state is referred to as “render safe” or “safing.”

Generically speaking, tests that involve high-energy, high-voltage capacitor banks anywhere from hundreds of kilo-Joules to tens of mega-Joules are charged by means of a high-voltage power supply and subsequently discharged through some form of switching network or device such as a Silicon Carbide Gate Turn-Off Thyristor (SGTO), Pulse Forming Network (PFN), Gas Tube, Traveling Wave Tube (TWT) or any number of other devices. If, during this process, the control system fails, the capacitor suffers an internal short circuit, the external buss bar structure develops a short due to magneto-restriction or some other adverse event occurs, then there is the distinct possibility that the capacitor bank did not fully discharge 100% of its energy. In this case the capacitor must be placed in a safe state either manually or by remote control. To safely remove the energy from a capacitor with an energy storage that is rated greater than 10 kJ, a remotely operated discharge system utilizing an appropriately rated discharge resistor should be utilized. If the remote discharge circuit fails due to some anomaly, then the bank must be manually discharged. This involves a worker approaching the capacitor bank and physically shorting the capacitors utilizing preapproved discharge sticks, thus exposing the worker to the dangers of electrocution, burns from an electrical arc, burns from flying molten metal, shrapnel, and injury from an acoustic over-pressure.

Protection from electrocution, arc flash, molten metal and shrapnel is provided by personnel protection equipment (PPE), engineering controls, and administrative controls. However, there has been little guidance on the hazards and protections associated with an acoustic over-pressure from an arc blast. To establish some guidance for this oversight, a very conservative assumption is made: the stored energy of a capacitor bank is equated to the energy of a trinitrotoluene (TNT) blast. Given this assumption, a ConWep computer model was utilized to calculate the distance from the blast as a function of the TNT energy that would produce a 1% probability of rupturing the eardrum, and another distance that would produce a 1% probability of lung damage. These TNT distances are then compared to the boundaries recommended by electrical safety experts relative to capacitor shock and arc flash hazards. When comparing these two distances (TNT

versus capacitors electrical energy) it was determined that the distance for an arc flash incident energy exposure of 1.2 cal/cm^2—the threshold for second degree burn to exposed skin—is greater than the distance for the 1% probability of lung damage, but well within the distance for the 1% probability of eardrum damage. A proposed guide line is to remain outside the restricted boundary as defined by this 1.2 cal/cm^2 defined arc flash distance. Accordingly, by prescribing to this limit, the use of arc flash PPE is no longer an issue and is not applicable, except in the event of a catastrophic incident. Although arc flash PPE would no longer be necessary, hearing protection must be utilized accordingly.

In the rest of the report, a review of the limited number of experiments and calculations is given that show only a fraction of the stored energy is converted to acoustic energy. Next is a description of the injuries that result from an over-pressure and how the distances from the arc to prevent these injuries were estimated as a function of the stored energy. Finally, the guide line for the arc flash is reviewed, since it is used to establish the distance of closest approach that will also protect the worker from lung injury.

2. Shock Wave

Most of the documented experiments that measured the over-pressure produced by an electrical arc were to simulate lightning and thunder. Thus, they were designed to produce long electrical arcs from a high-voltage source but at currents on the order of 10^4 amps, while current in a discharge from a high-energy capacitor bank could be on the order of 10^6 amps. The over-pressure from a 0.185-m long arc generated by a Marx bank was measured at different distances from the arc (*1*), when the Marx bank had a stored energy of 1.25 kJ, 2.5 kJ, 4.4 kJ, and 6.0 kJ. The acoustic energy at each of the stored energy levels was implied from the over-pressure. It was observed that the acoustic energy was about 40% when the stored energy was 1.25 kJ. This percentage decreased as the square of the stored energy to 18%, when the stored energy was 6.0 kJ. Unfortunately, the current in these experiments was not measured. In another study, a 4-m long arc (*2*) was formed by a 6.4-MV impulse generator that delivered 20 kJ to the arc. Again the over-pressure was measured at various distances from the arc to infer the acoustic energy, which was roughly 16% of the delivered energy. In this study, the energy to the arc was not varied. In an experiment that studied the energy losses in a spark-gap switch (*3*), an over-pressure in the spark gap was measured, when it conducted a peak current of 520 kA from a 2.0-MJ capacitor bank that was fully charged to 24 kV. The over-pressure (400 psi) was measured at only one distance (11 cm) from the arc and the pressure data for just one case was presented. It was still possible to estimate that the acoustic energy in the spark-gap switch was about 20 kJ for a 1-cm gap, while the total energy loss in the spark-gap switch was about 100 kJ. This gives 20% for the acoustic energy. A numerical simulation (*4*) was conducted for a current that reaches a peak of 28 kA in 5.6 μs. A graph in this paper shows that the kinetic energy of the gas was always less

than 10% of the total energy delivered to the arc for the entire time of the pulse. Thus, the energy of the shock wave is only a fraction of the total energy and the assumption that all of the stored energy is converted to acoustic energy is very conservative.

The reason why only a fraction of the total energy is coupled to the shock wave is complicated (*5*). A very simplistic explanation, however, is to assume that the outside radius of the arc channel acts like an expanding solid cylinder. When the arc channel just forms, its radius could be microscopic. With the increasing current, however, the radial velocity of the arc channel can be supersonic, which produces a shock wave. As the arc channel expands, its radial velocity decreases to subsonic speeds when its expansion can no longer support the shock wave. What is left behind is a relatively slow expanding conducting channel of very hot gas (25,000–30,000 K) at low density and near ambient pressure (*4*). Indeed, if the current is large enough, the arc channel may be contracted by the magnetic field of the current (*6*).

3. Blast Barotrauma

The shock wave from blast is a very sudden increase in the air pressure in the form of an over-pressure that is traveling faster than the speed of sound. The maximum pressure in the shock wave depends on the energy of the source: higher energy of the source produces higher pressures. This sudden increase in pressure produces an imbalance of pressure in the body and causes injury. As an example, the eardrum membrane may break if the outside pressure suddenly increases to 3 psi over the atmospheric pressure while the other side of the eardrum is still at atmospheric pressure. Other injuries to the ear are also possible. Lungs are the next vulnerable organs that are injured by being violently collapsed at higher over-pressures (greater than about 10 psi). Since this pressure decreases as it travels away from the source, injuries can be avoided by being some safe distance away from the source.

The first step to find the safe distances for the ear and for the lungs, is to establish the over-pressure as a function of the energy of the source and the distance from the source. This is done by assuming that an amount of TNT having the equivalent energy as the stored energy of the capacitor bank is detonated on the ground. A blast being directed by an open cabinet, as an example, was not considered. It is then assumed that the human target is standing and facing the detonation, which is worst-case posture. A safe distance for the ear is when the over-pressure is less than 3 psi, where there is a 1% probability of eardrum rupture (*7*). ConWep was used to calculate the distance for this over-pressure at various stored energies. Calculating a safe distance where there is a 1% probability of lung damage is complicated by the duration of the over-pressure, but the Air_Blast_Lethality code was still used to find this distance at various stored energies. The loading model in the Air_Blast_Lethality (*9–11*) code is similar to BlastX (*12*) and has been validate against Sandia's shock code CTH (*13*) hydrocode runs. The lung injury model

is based on blast injury model in Operational Requirement-Based Casualty Assessment (ORCA) (*14*) code. The model in ORCA is in turn based on INJURY (*15*) model.

The mass of TNT involved in these calculations is very small compared to the amounts used in Air_Blast_Lethality code validation testing. Because the model was used with a charge much smaller than those assumed in code, testing the results should be viewed with caution. The results from these calculations, the black squares in figure 1, were then fitted to empirical formulas, where E in all of these formulas is the stored energy in kilo-Joules and the distances are in centimeters. The regression formula for the safe distance for the ear is

$$R_{ear} = 49.29E^{1/3} - 5.09. \quad (1)$$

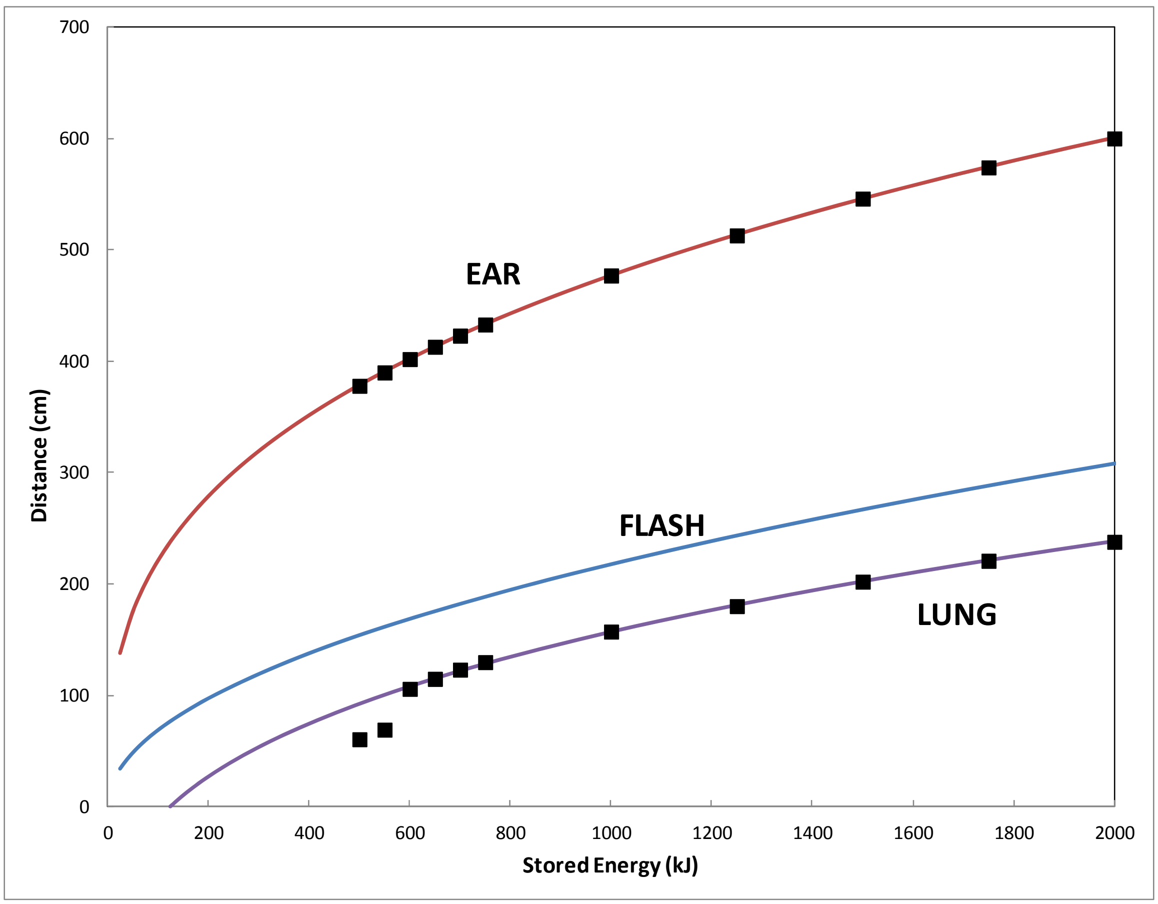

Figure 1. Injuries from an arc blast; "EAR" is 1% probability of ear damage, "FLASH" is the threshold for second-degree exposed skin burn (1.2 cal/cm^2), and "LUNG" is 1% probability of lung damage, ■'s are ConWep and Air_Blast_Lethality distances.

This distance is plotted in figure 1 as "EAR" along with the ConWep calculations as shown by the solid squares. The formula for the safe distance for the lungs is, plotted in figure 1 as "LUNG", is

$$R_{lung} = 31.32E^{1/3} - 155.45 \quad (2)$$

for stored energies greater than 122 kJ, and zero for lesser energies, but the NFPA-70E 2012 “Prohibited Approach Boundary” for shock must still be observed. The distance for the lungs is plotted in figure 1 as “LUNG” along with the results from the Air_Blast_Lethality code as shown by the solid squares. This formula gives slightly larger distances than those from the Air_Blast_Lethality code at energies less than about 650 kJ, and reproduces the codes results at higher energies. The larger distances at the lower energies are acceptable for safety reasons.

4. Arc Flash

To calculate the exposure from an arc flash (*16*), it is also assumed that all of the stored energy is converted to the radiant energy of the arc flash, and then spreads out over a spherical area

$$D = \frac{3000\,E}{4\pi 4.184 R_{Flash}^2} \,. \tag{3}$$

D is the incident energy dose in calories per square centimeter. The factor 4.184 has a unit of Joules/calorie. The stored energy E is multiplied by 3.0 to account for the possibility of the arc flash being directed by an enclosure, such as an open cabinet, and 1000.0 to convert its unit from kilo-Joules into Joules. Thus, the distance for a given dose is then

$$R_{Flash} = 7.6\sqrt{\frac{E}{D}} \,, \tag{4}$$

This distance is plotted in figure 1 as “FLASH” when $D = 1.2$ cal/cm^2.

Given the assumptions so far, the arc flash distance is a safe distance for the lungs, but it is within a distance where there is a probability greater than 1% for ear injury. Now assume that only a fraction of the stored energy is converted to acoustic energy, which will decrease the safe distances for the ear and the lungs. This assumption, however, does not change the flash distance, since it is set by the assumed radiant energy of the arc. In figure 2, the safe distance for the arc flash is well within the distance for possible ear injury, even when only 25% of the stored energy is converted to acoustic energy. Thus, hearing protection must always be used. In figure 3, the safe distance for the flash is obviously always a safe distance for lung injury. It also shows that the safe distance to avoid lung injury quickly decreases as the conversion percentage decreases.

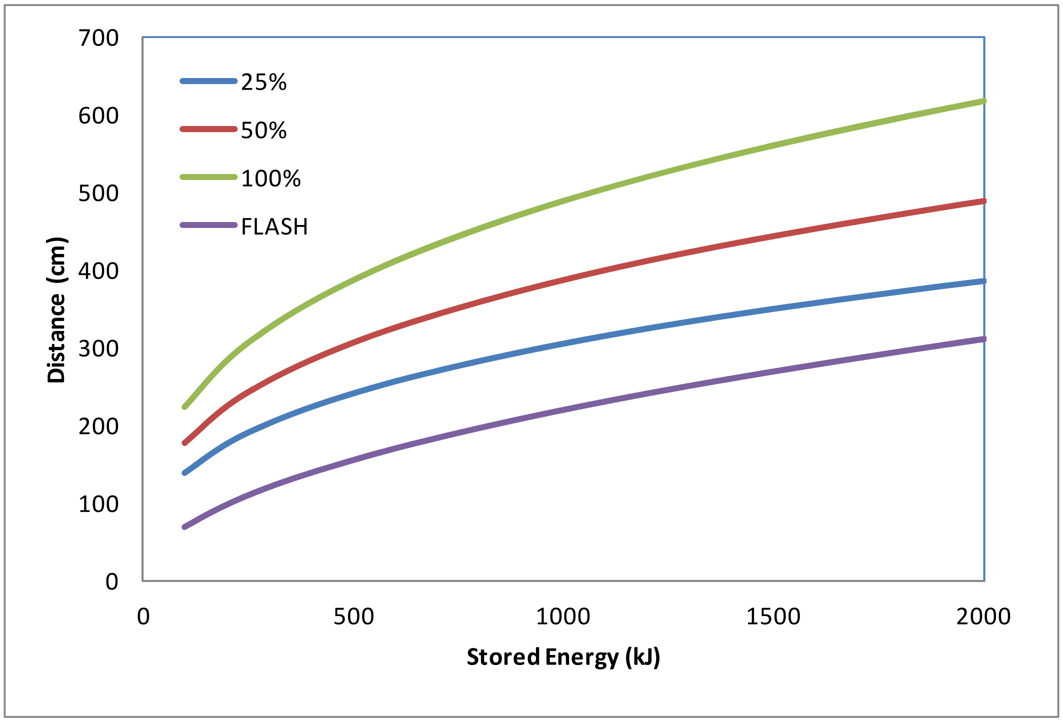

Figure 2. Ear injuries from an arc blast with different acoustic conversion percentage.

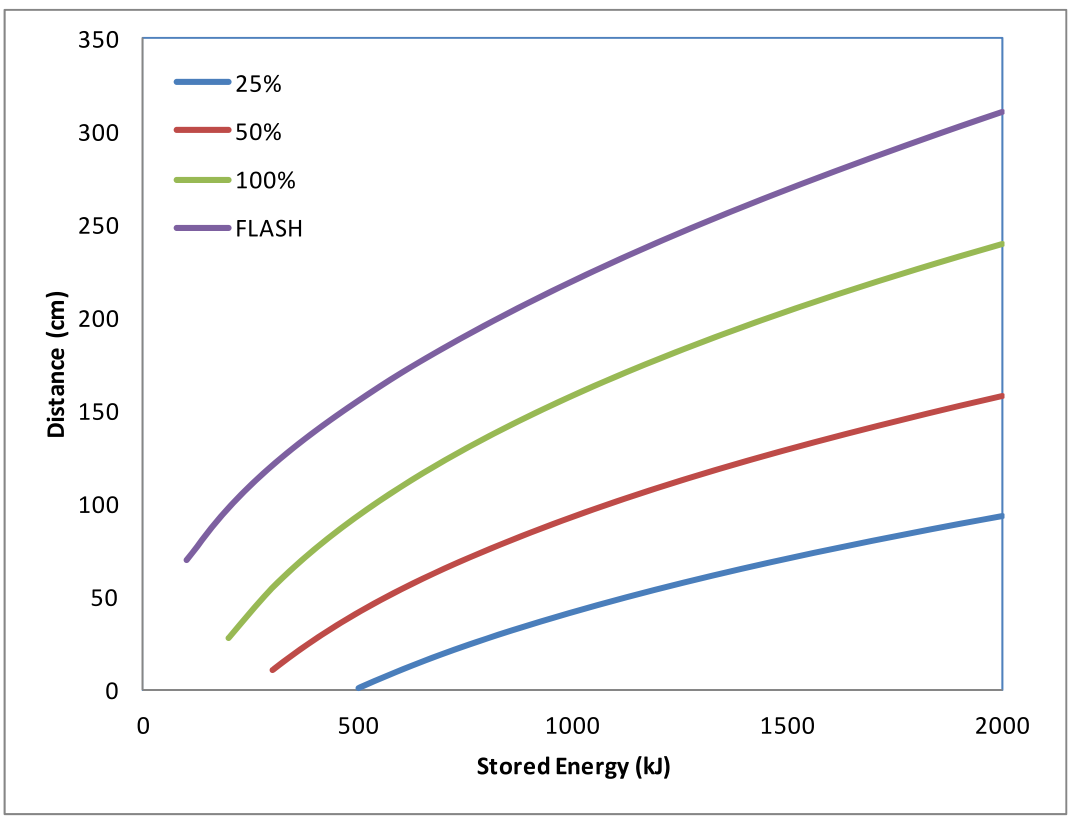

Figure 3. Lung injuries from an arc blast with different acoustic conversion percentage.

5. Conclusions

Due to the distance required to prevent lung damage from a potential over-pressure from an arc blast, the arc rating of the PPE should NOT be used to establish the “Prohibited Boundary” for safing high-energy capacitor banks, which is contrary to the widely held assumption. It should be noted that this distance does not take into account the potential for flying debris in the event that a capacitor suffers a catastrophic failure. Although some protection may be intrinsically afforded by arc rated PPE against flying debris and over-pressure, it is not tested or rated for these conditions and should NOT be utilized as such. Until more research is completed the “Restricted Boundary” as determined by the threshold for second-degree exposed skin burn should be deemed as the overall safety “Prohibited Boundary” for high-energy capacitor banks. Furthermore, it is noted that this distance is always within the distance where there is a probability greater than 1% for ear injury. Therefore, hearing protection should be worn at all times. A comprehensive hazard analysis should define not only the shock and arc flash boundaries, but boundaries for lung and ear damage as well.

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